Torsion pendulum investigation of thermal gradient-induced forces on LISA test masses

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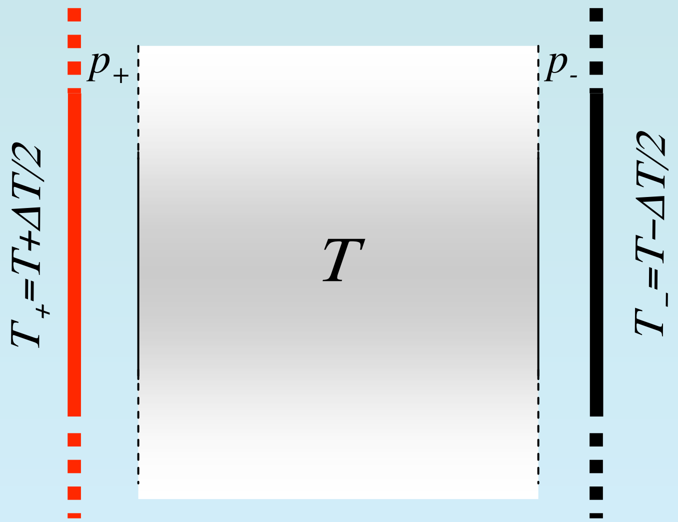
Talk summary

- Thermal gradients on LISA Test Masses
- Investigations on representative LISA GR sensors
  different geometries and construction techniques
- Scheme of the torsion pendulum experiments
- Effects evaluation
  - estimate of the effects
  - comparison with model
- Conclusions
- Forthcoming experiments

Thermal gradients on LISA Test Masses

- Test Mass acceleration noise must be minimized
- Among other effects, thermal fluctuations will be increasing at low frequency

Basic linearized model



$$F_{radiom} = A\frac{P}{4}\frac{\Delta T}{T}$$ Radiometric effect

$$F_{rad\ press} = A\frac{8\sigma}{3c}T^3\Delta T$$ Radiation pressure

$T = 293$ K $\quad F_{radiom} = F_{rad\ pres}$ for $P = P^* \approx 15$ μPa

LISA envisioned thermal gradient stability

$$S_{\Delta T}^{1/2} \approx 10\frac{\mu\mathrm{K}}{\sqrt{\mathrm{Hz}}}$$

$$S_{F_{\Delta T}}^{1/2} \approx 0.5\frac{\mathrm{fm}}{\mathrm{s}^2\sqrt{\mathrm{Hz}}}$$

$$F_{outgas} \propto G\frac{\Delta T}{T^2}\Theta Q_{outgas}(T,\Theta)$$

- Outgassing parameters Q_{outgas} and Θ difficult to predict (virtual leaks, impurities, geometrical parameters G…)

LISA GRS characterization

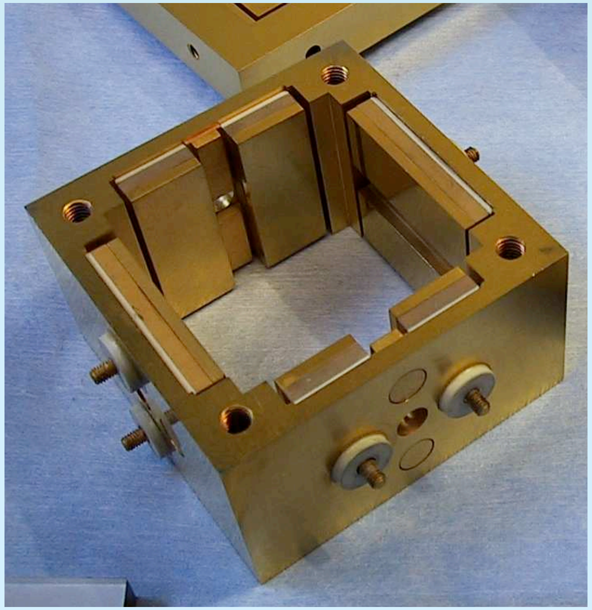
Need to measure *dF/dΔT* in representative configuration
to search for any excess coupling to a temperature gradient

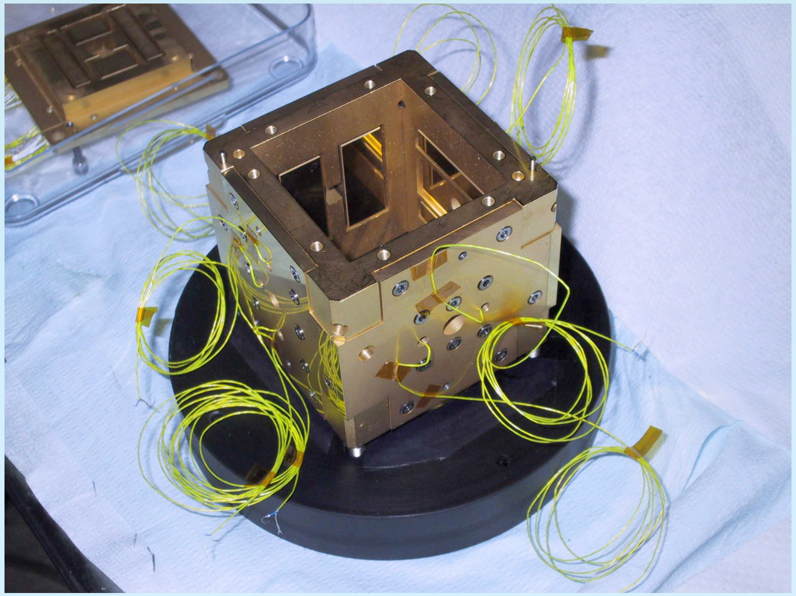
“TN” prototype:

- 2 mm gaps
- bulk Mo electrodes, Au-coated
- SHAPAL spacers
- glued on support

LTP sensor (Engineering Model Replica):

- 4 mm *x* gaps, 2.9 *y* gaps
- Au-coated electrodes on SHAPAL insulators
- bolted on support





Torsion pendulum characterization of LISA sensors

Verification of physical mechanism models and parameters measurement

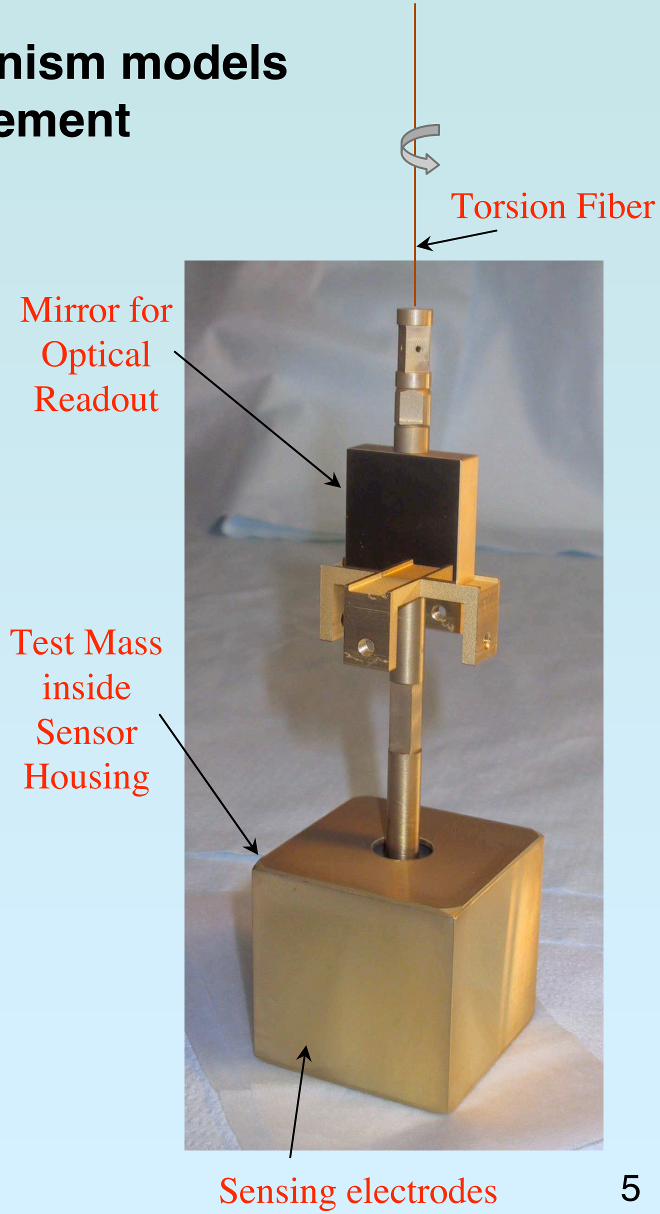
Key instrument of this testing effort are **torsion pendulum benches**:

torsion pendulum with a hollow replica of the TM inside the GRS

Place upper limit on force disturbances related with GRS and TM surface properties

Characterization of individual disturbance sources

Many more details in poster by D. Tombolato *et al*



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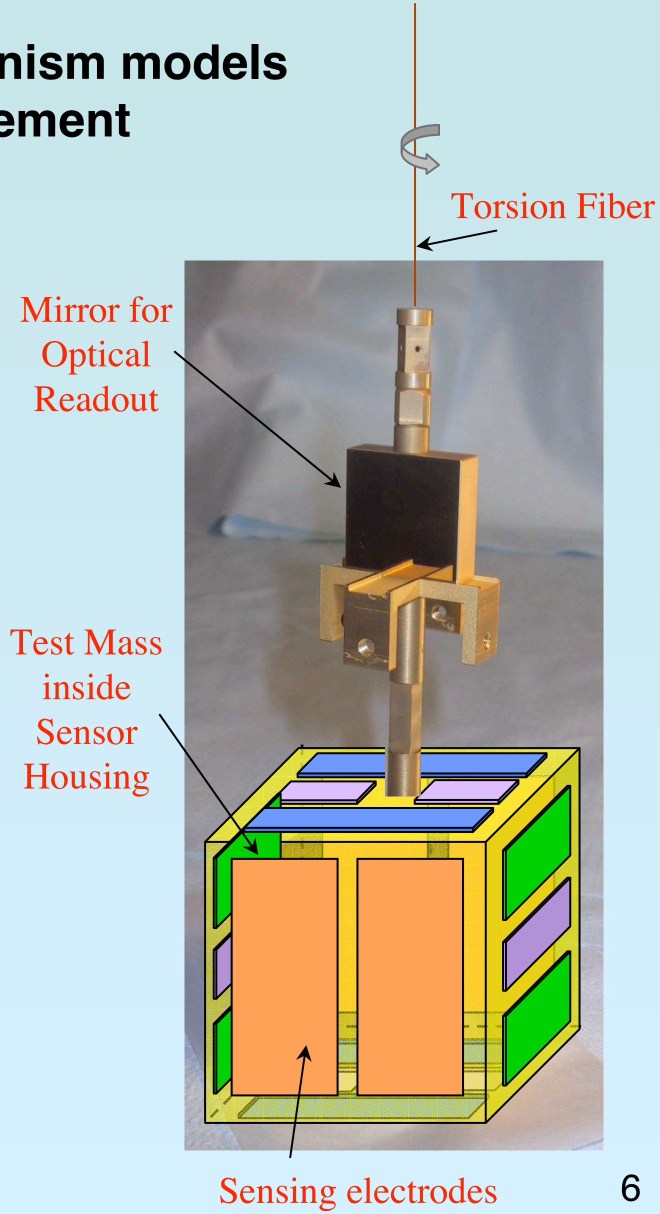
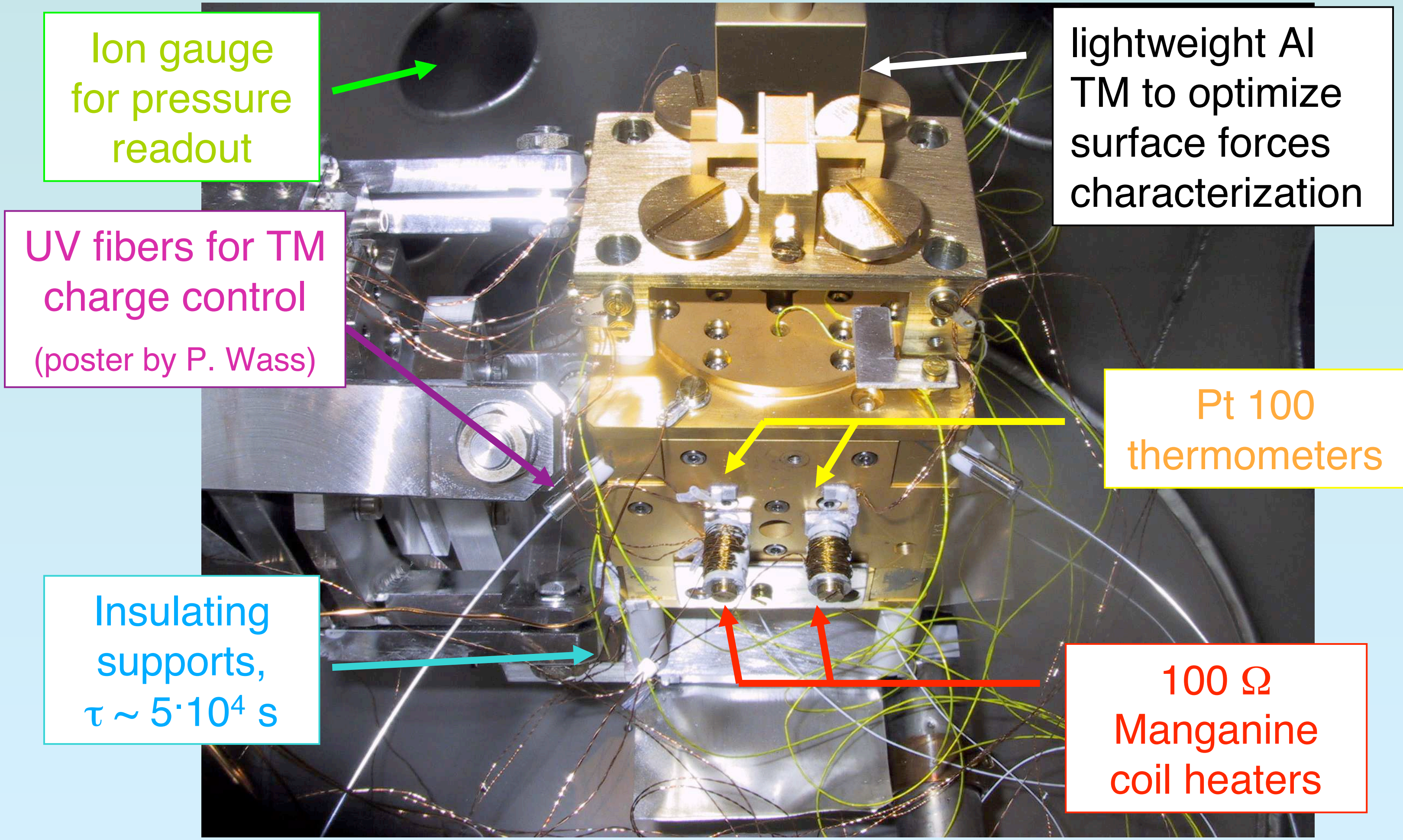
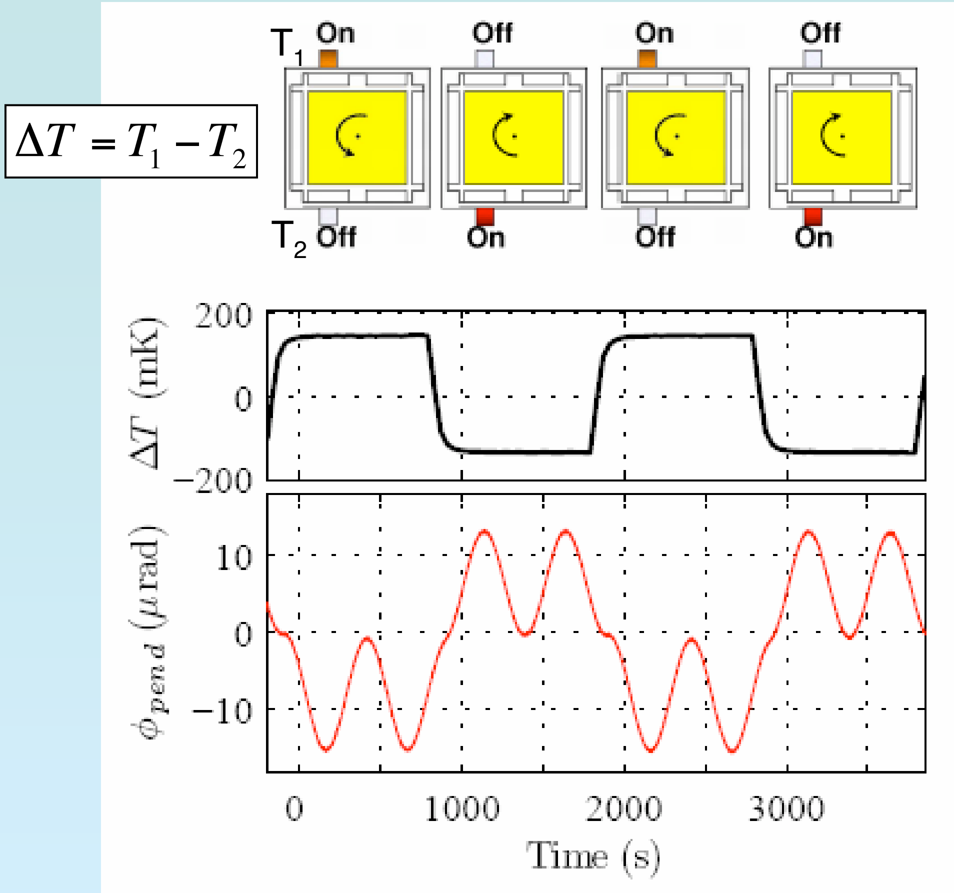
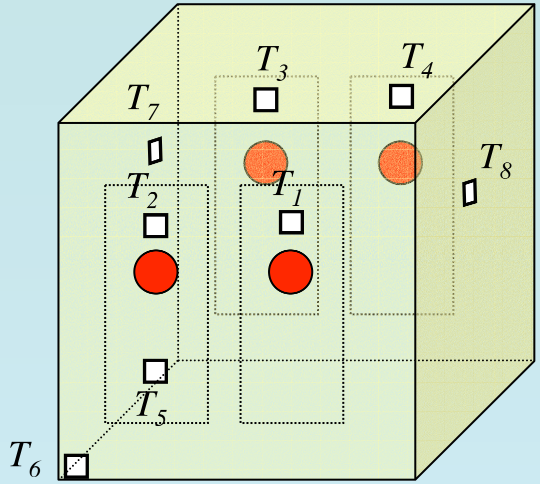


LISA Sensors integrated in the facility



Experimental technique

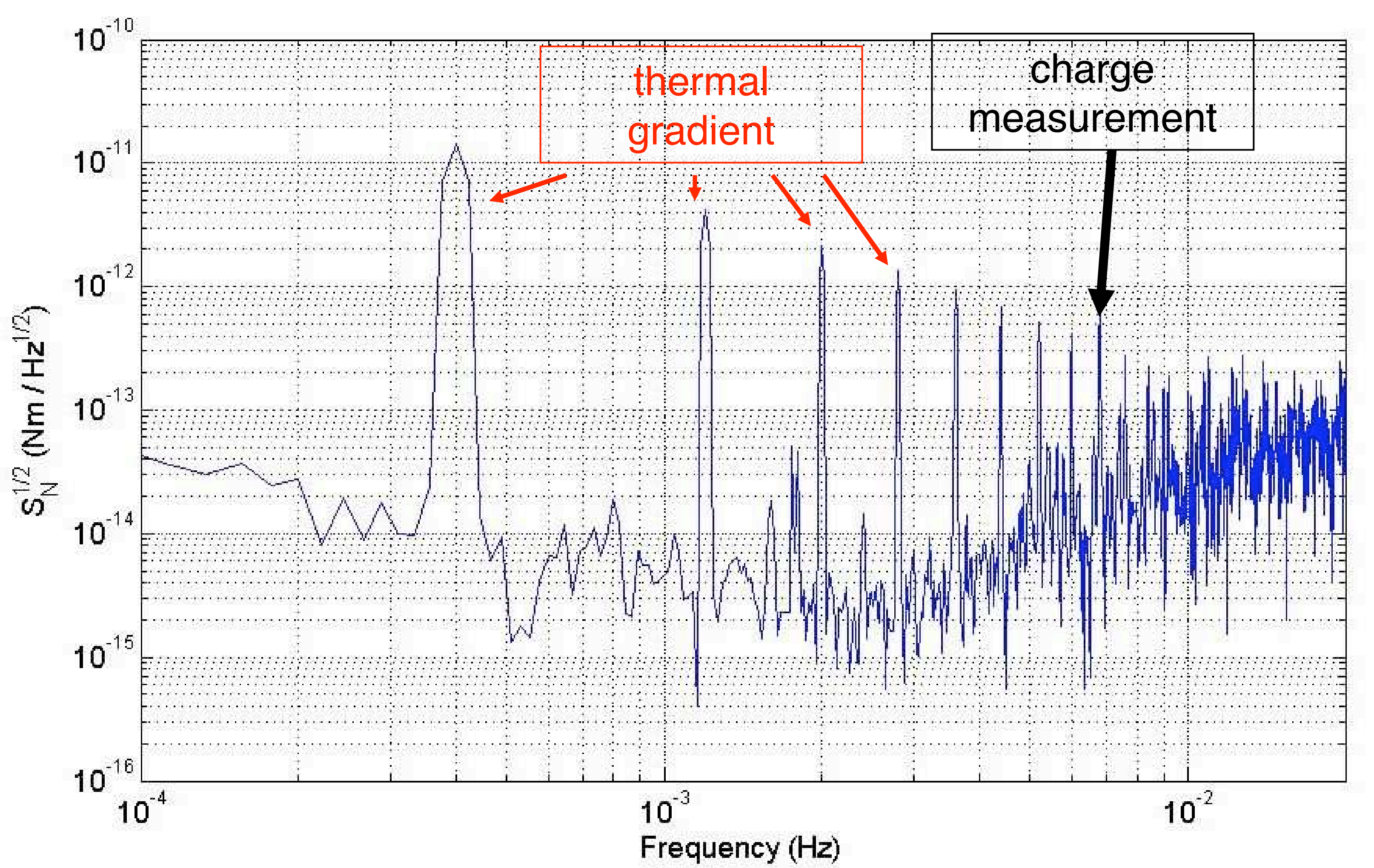




- *T* patterns measured by an array of Pt100 thermometers
- 300 mW typical power
- *P* controlled by turbo pump and valve from $2.5 \cdot 10^{-6}$ Pa to $1 \cdot 10^{-4}$ Pa
- *P* measured by UHV ion gauge

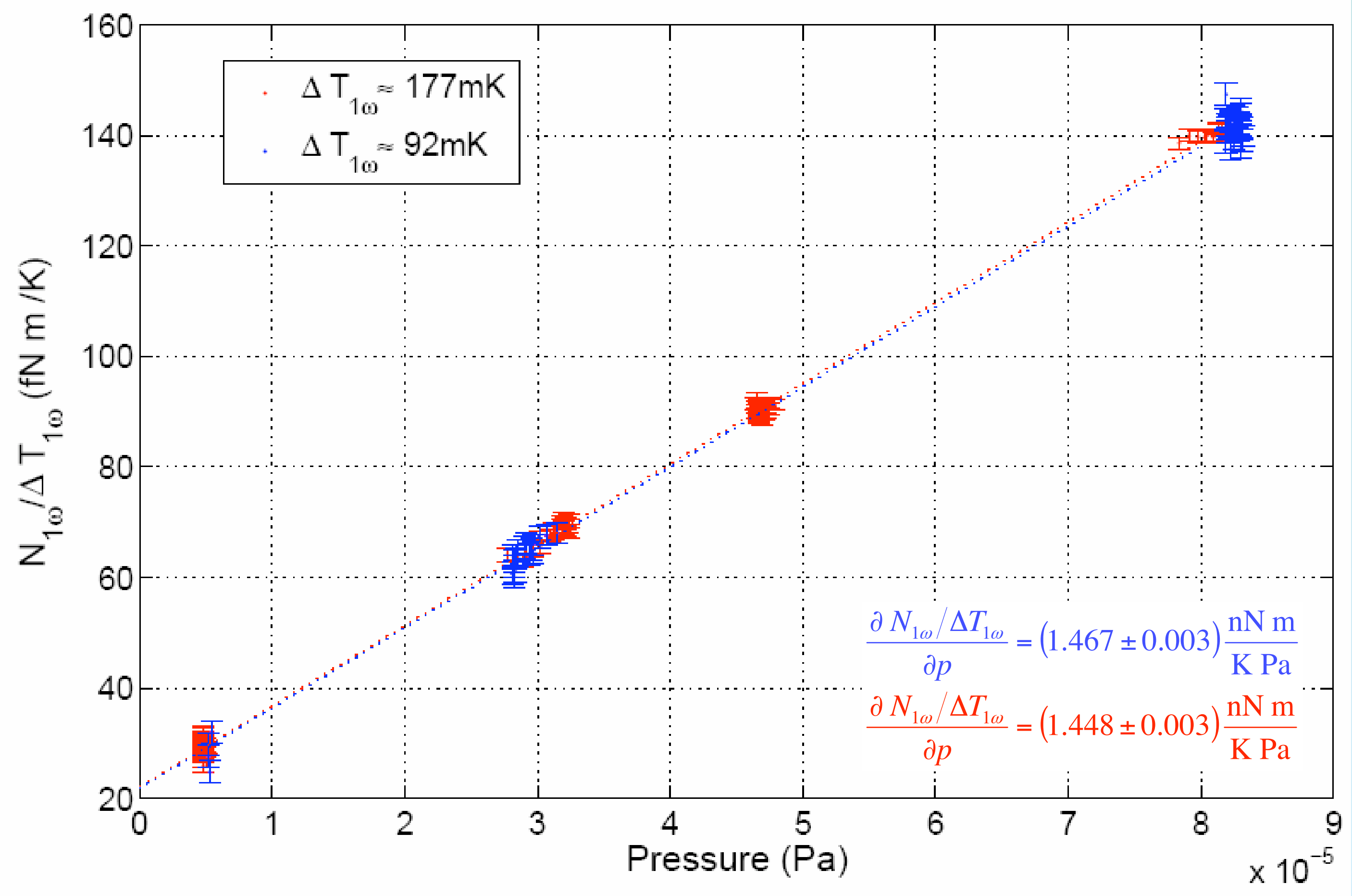
- Applying oscillating temperature patterns by alternating heaters
- Searching for coherent pendulum deflection to measure the induced torque
- Demodulation technique searching of coherent temperature and torque signals

Experimental technique



- 1st harmonic signal at 0.4 mHz, torque resolution <0.1 fN m
- TM electric charge kept constant by UV light

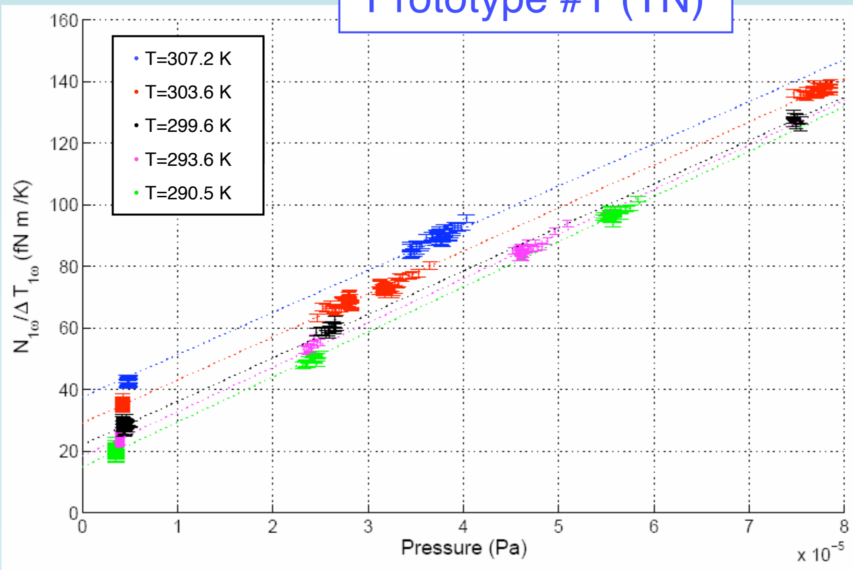
Experimental results: dependence on pressure



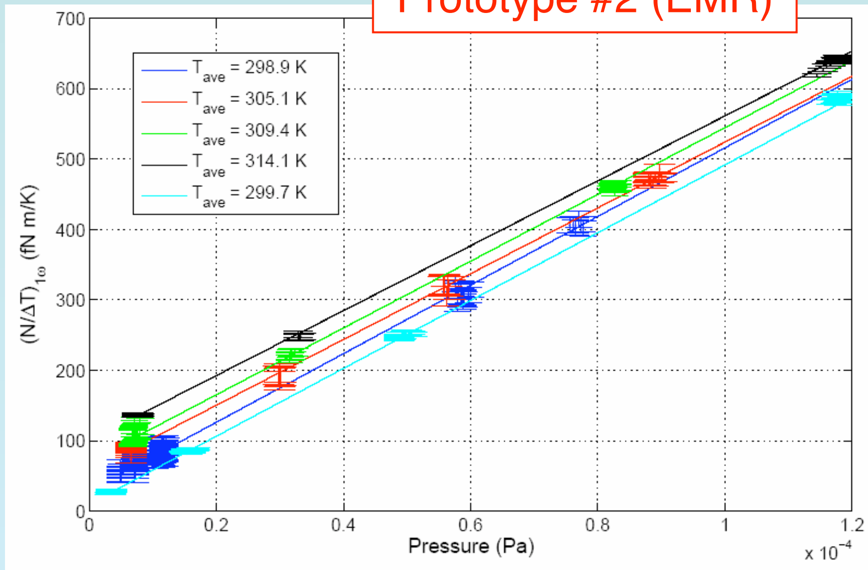
- Torques scale with representative gradient ΔT
- Torques depends linearly on pressure

Experimental results: dependence on temperature

Prototype #1 (TN)



Prototype #2 (EMR)



Measurement of induced torque as function of

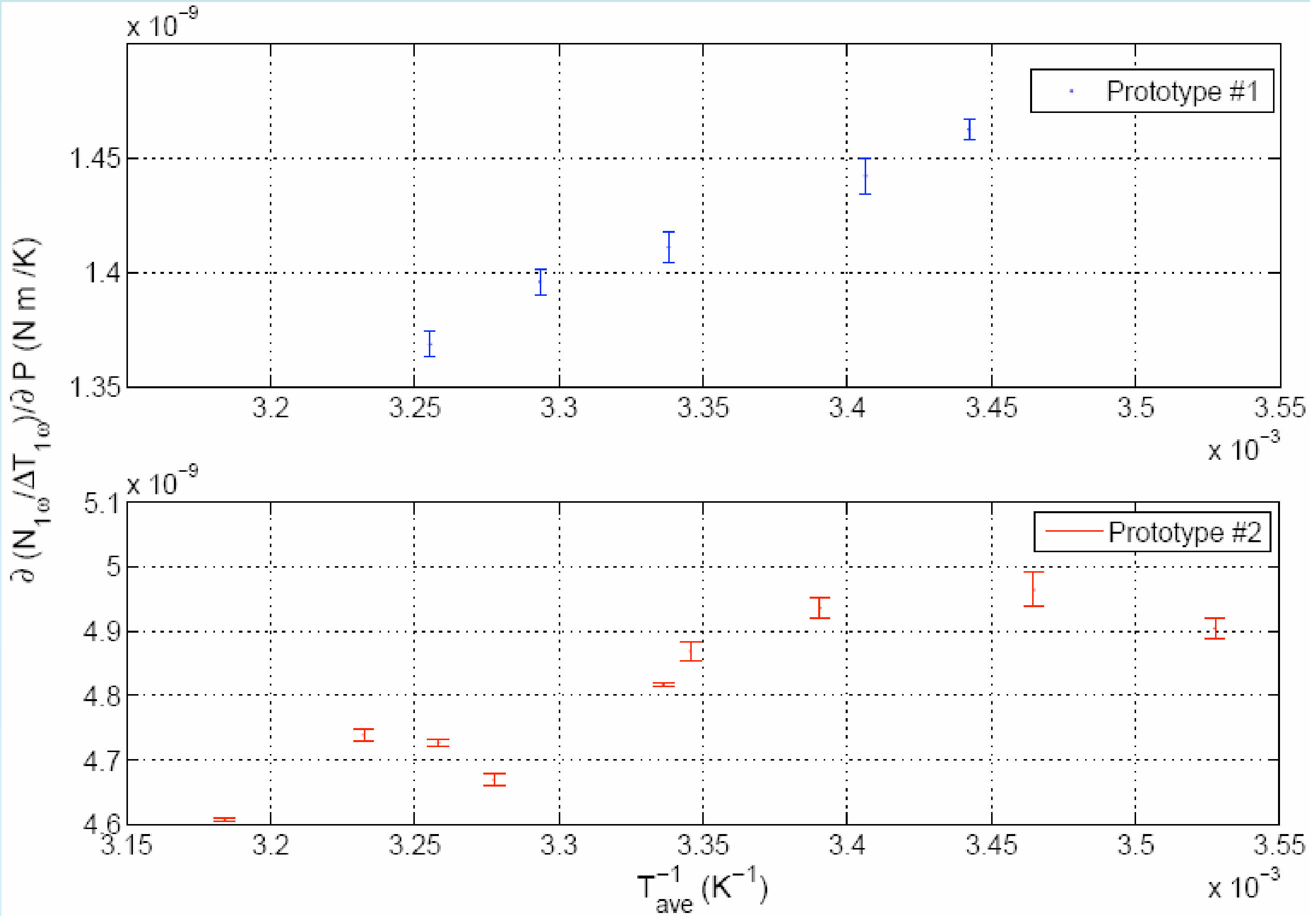
- measured pressure P
- average sensor temperature T_{GRS}

Search for temperature gradient induced torques in excess of that expected for radiometric and radiation pressure effects

$$\begin{cases} N_{radiom} \propto \Delta T \dfrac{P}{T_{GRS}} \\ N_{rad\ press} \propto \Delta T \cdot T_{GRS}^{3} \\ N_{outgas} \propto \Delta T \dfrac{\Theta Q_{outgas}(T_{GRS})}{T_{GRS}^{2}} \end{cases}$$

Radiometric effect: slopes

$$\frac{\partial N_{radiom}}{\partial P} \propto \frac{1}{T_{ave}}$$



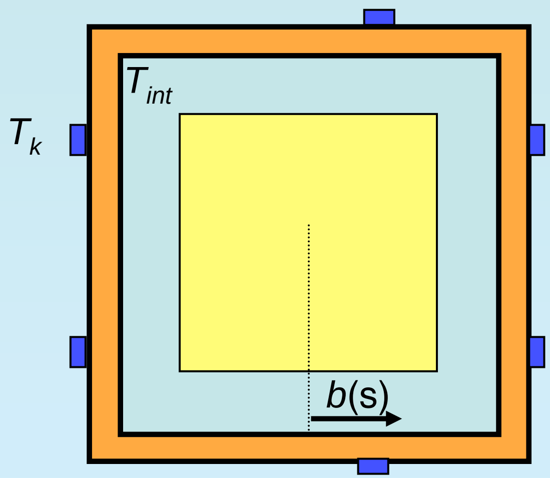
Modeling

Expected torque about torsion axis estimated from

$$N_{radiom} = \frac{P}{\left(4\overline{T}_{\mathrm{int}}\right)} \int_S T_{\mathrm{int}}(\mathrm{s})\, b(\mathrm{s})\, \mathrm{ds}$$

Local forces multiplied by arm-length

$$N_{rad\ press} = \frac{2\sigma}{c} \int_S T_{\mathrm{int}}^4(\mathrm{s})\, b'(\mathrm{s})\, \mathrm{ds}$$



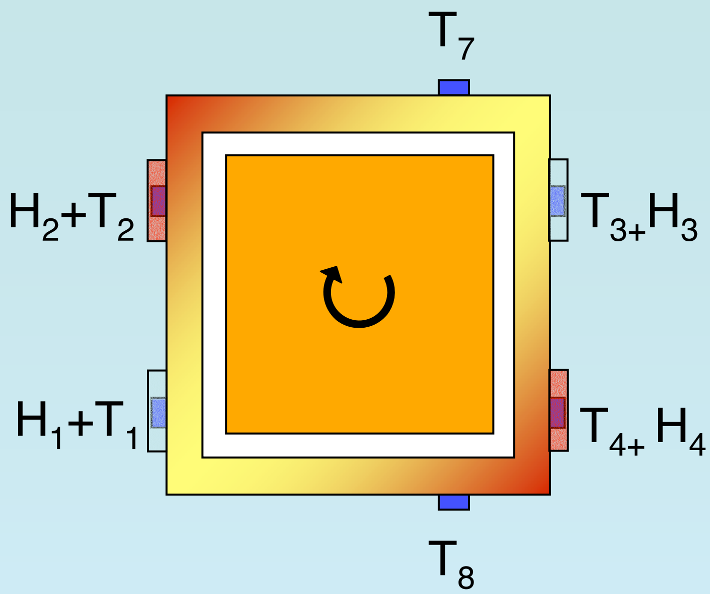
Simplified model
(no border effects)

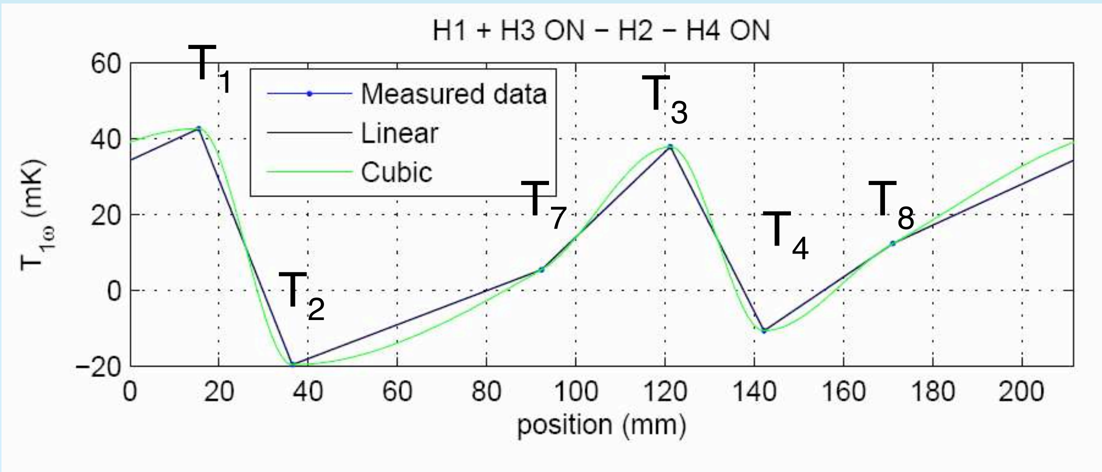
$$b(s) = b'(s) = y \qquad \left(-\frac{s}{2} \le y \le \frac{s}{2}\right)$$

Representative gradient is $\Delta T = \sum c_k T_k \propto \int_S T_{\mathrm{int}}(\mathrm{s})\, b(\mathrm{s})\, \mathrm{ds}$

Estimate of temperature patterns

- Real LISA geometry, closed sensors (*y* and *z* faces)
- Need to account for all surfaces contributions
- Inner surface temperature profiles evaluated by interpolation of thermometer readings
- Vertical symmetry assumed
- Thermal model to asses this impact in progress, could give a factor ~2 effect

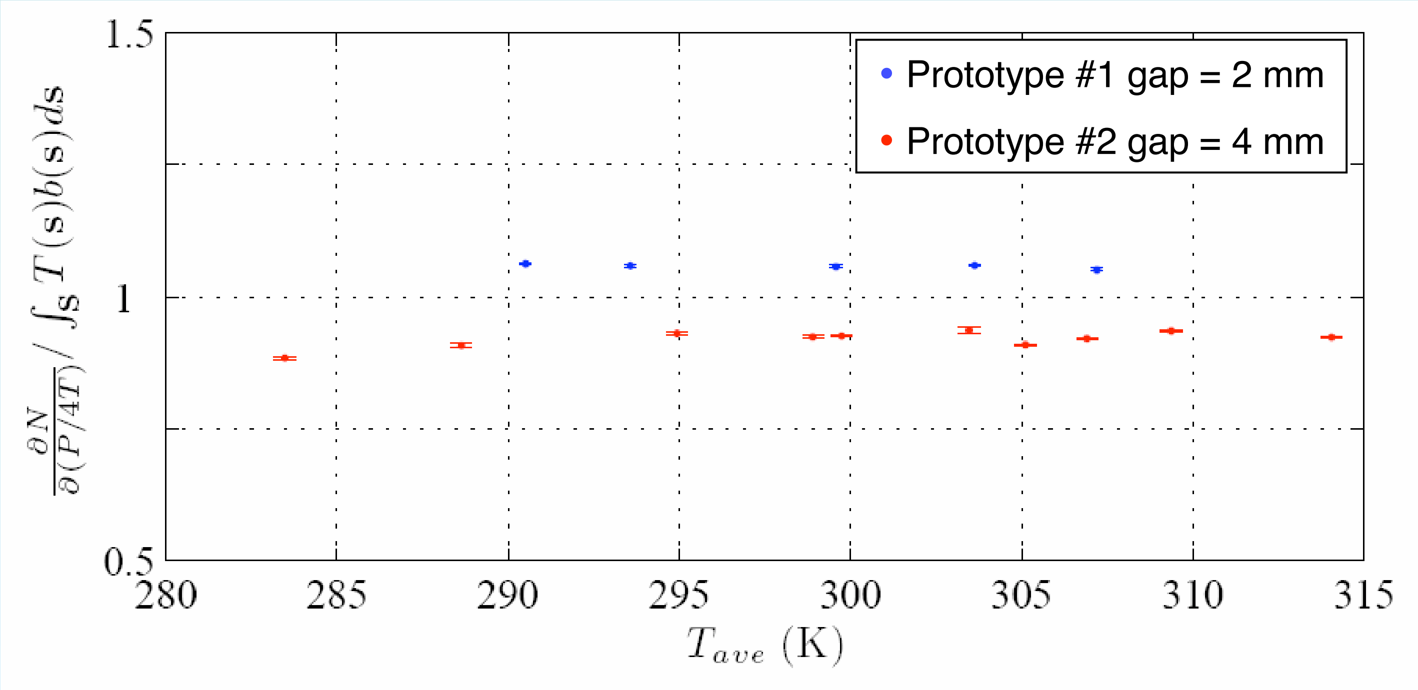




Radiometric effect for GRS prototypes

$$\frac{\partial N}{\partial (P/4T)} \frac{1}{\int_S T(s) b(s) ds} \approx 1$$

Simplified model
(ideal geometry, no boundary effects)



- Simulations and thermal modeling in progress for uncertainty assessment
- Simple radiometric formula for infinite plates still holds at 2 mm and 4 mm

Estimate of radiation pressure

$$\vec{F} = \sum_{\substack{TM\ faces \\ sens\ faces}} \int ds_1 ds_2\ \vec{f}(s_1, s_2)\left[T(s_1, s_2)\right]^4$$

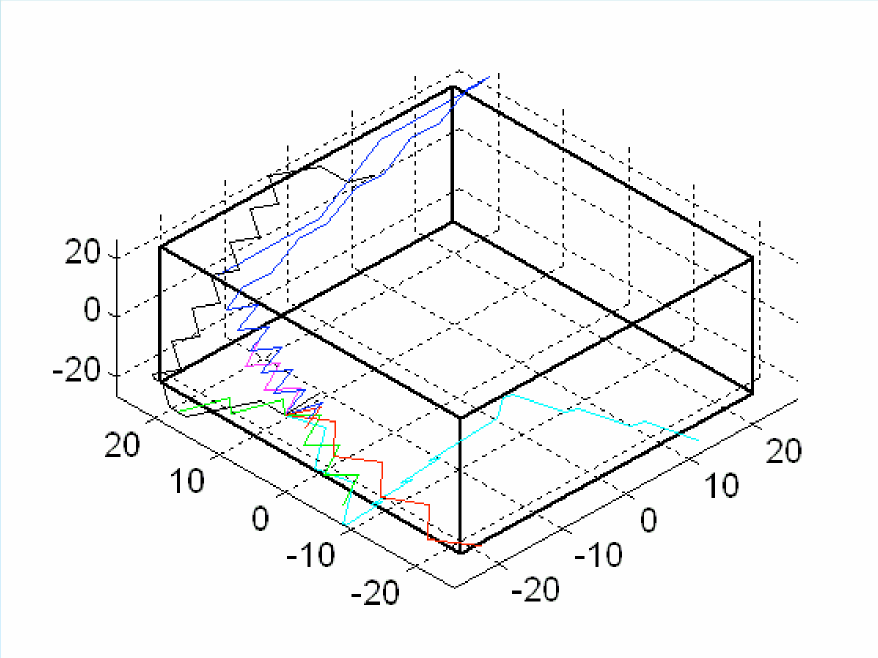
$$\vec{N} = \sum_{\substack{TM\ faces \\ sens\ faces}} \int ds_1 ds_2\ \vec{n}(s_1, s_2)\left[T(s_1, s_2)\right]^4$$

Calculate *f* and *n*:

- vectorial force (torque) per K^4 generated by thermal photons originating per element area in a certain position (s_1,s_2) on a given face of TM or sensor.

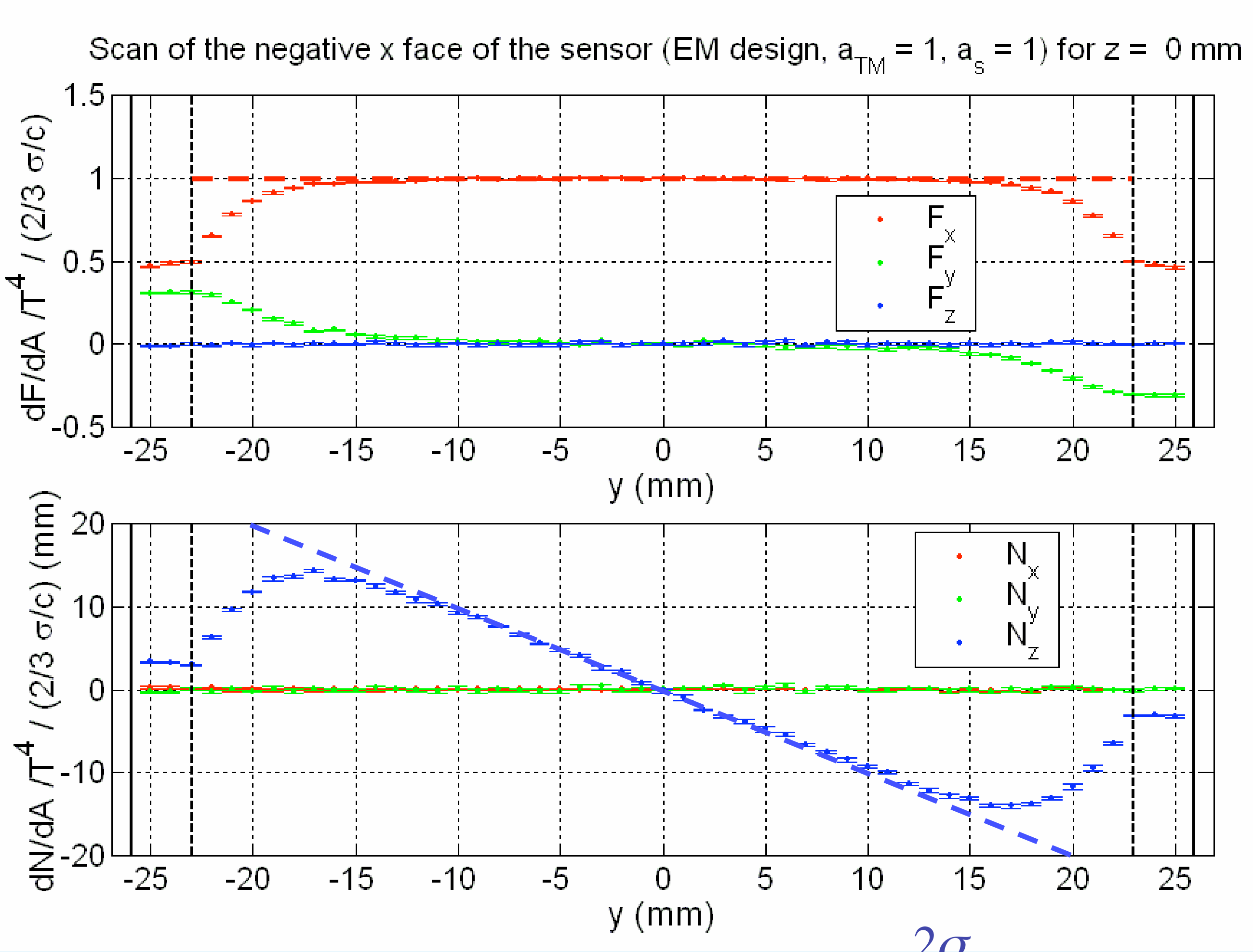
Assume:

- Sensor geometry (both prototypes)
- TM and sensor absortivity a_{TM} and a_{SENS} uniform on surfaces and in wavelength
- Reflection purely specular or diffuse



10 photons generated from $y = z = 0$ on the x- face of EM sensor, with $a_{TM} = a_{SENS}$=0.2

Border effects: no reflection



Increased force due to:
- finite TM size
- contributions from lateral surfaces

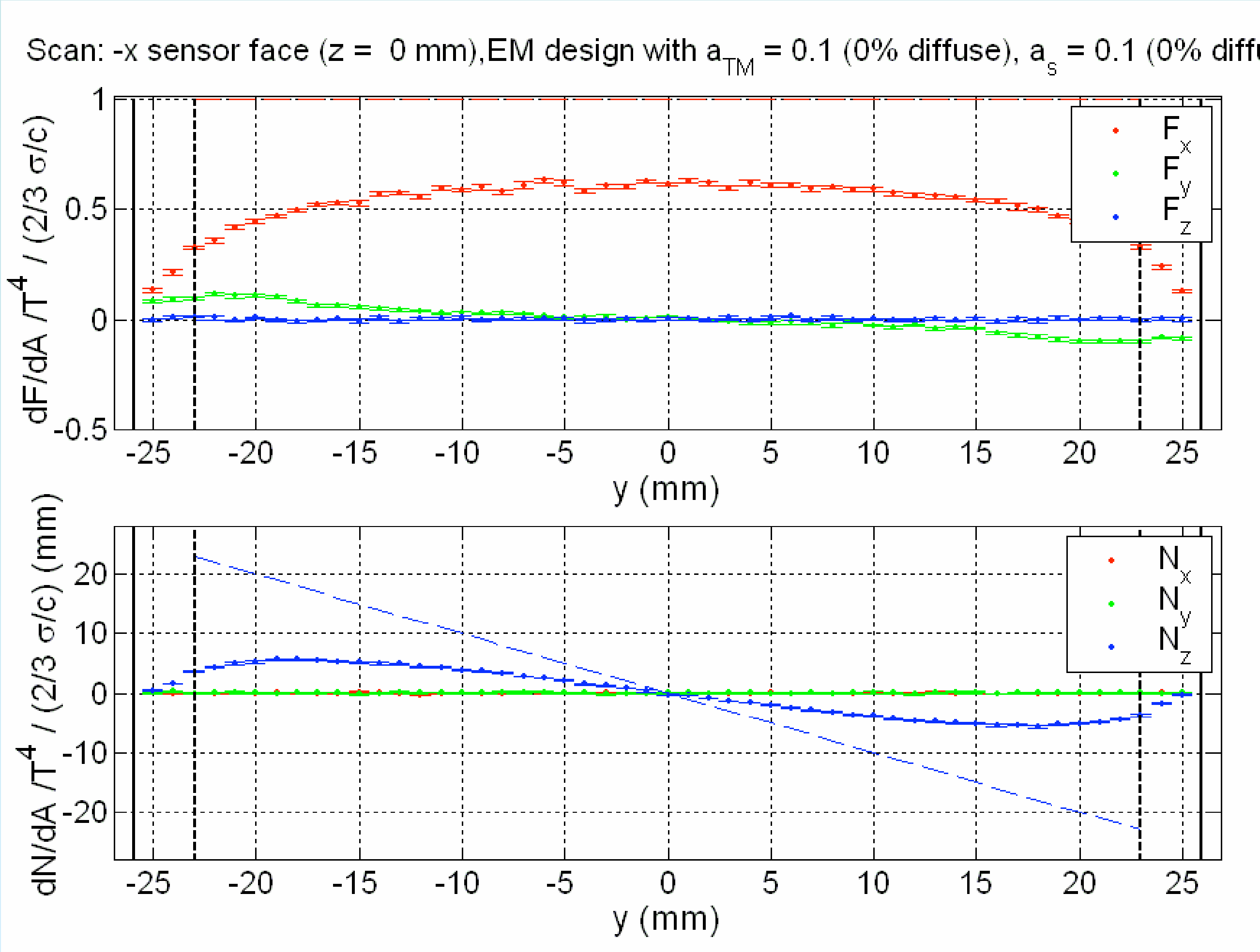
Decrease in torque due to finite TM size

For infinite parallel plates

$$f_x = \frac{2\sigma}{3c}$$

$$n_z = -\frac{2\sigma}{3c} y$$

Border effects: reflective surfaces



Suppression of force (for LISA!)

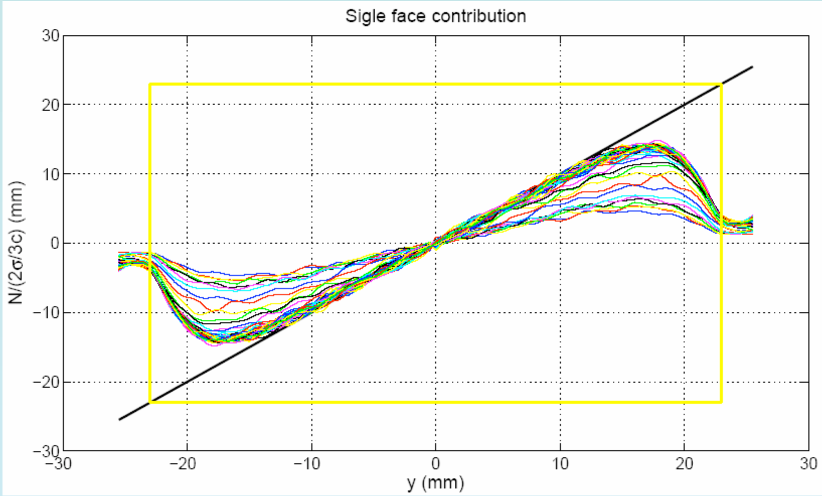
Suppression in torque

- Multiple reflections “dilute” the effect of photons emitted by each face

Evaluation of torque

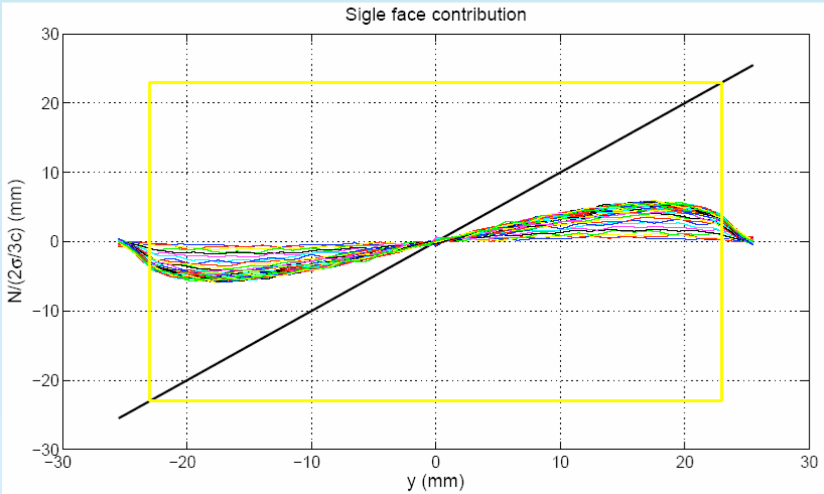
EMR geometry:

$a_S = 1$, $a_{TM} = 1$



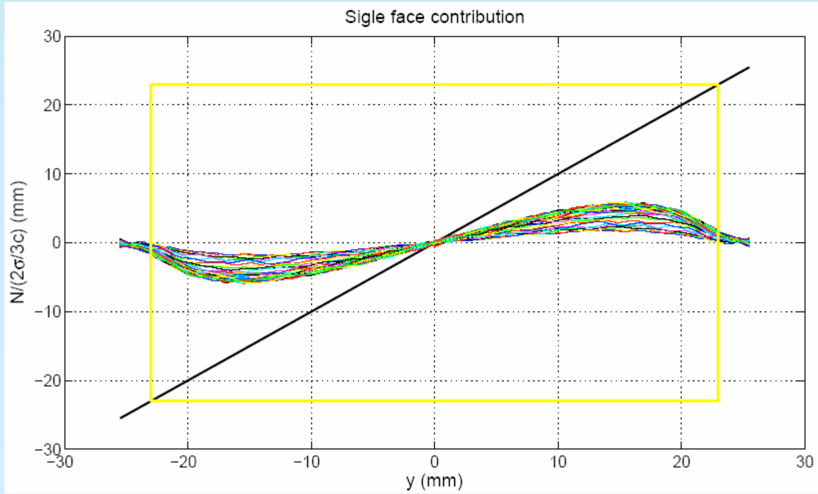
EMR geometry:

$a_S = 0.1$, $a_{TM} = 0.1$, $d = 0$



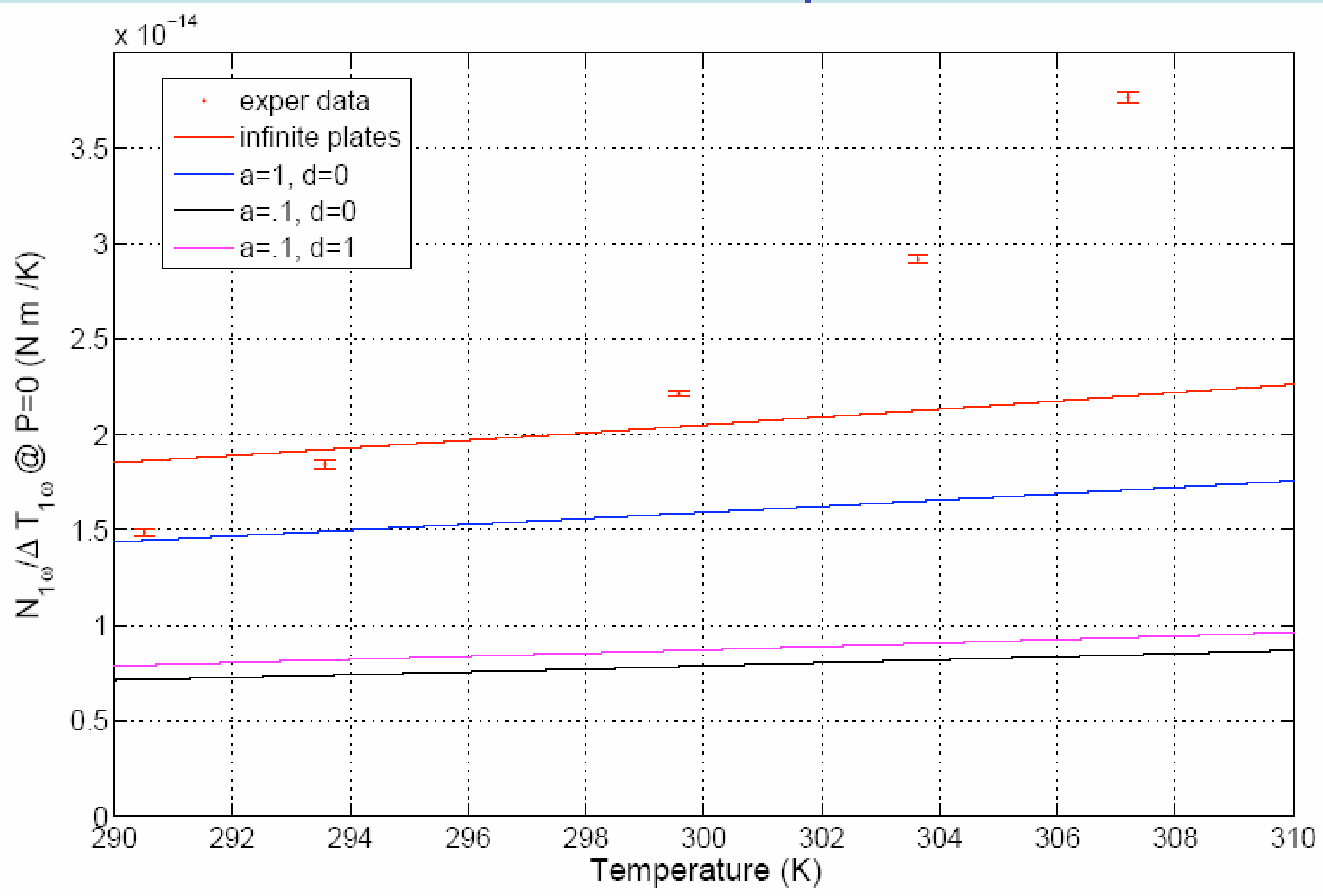
EMR geometry:

$a_S = 0.1$, $a_{TM} = 0.1$, $d = 1$



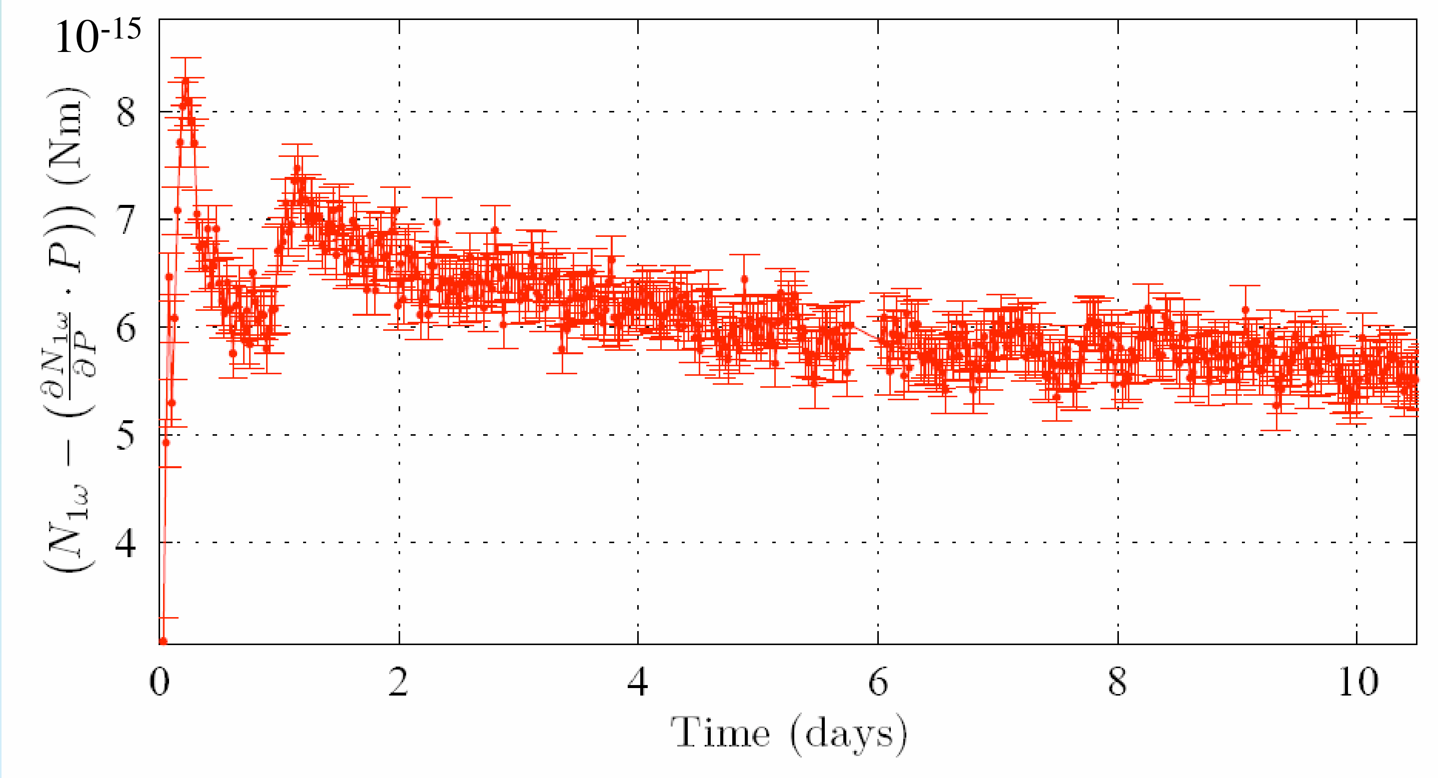
- Effective arm-length decrease while scanning the face about symmetry center
- Multiple reflections “dilute” the effect of photons emitted by each face

Residual torque



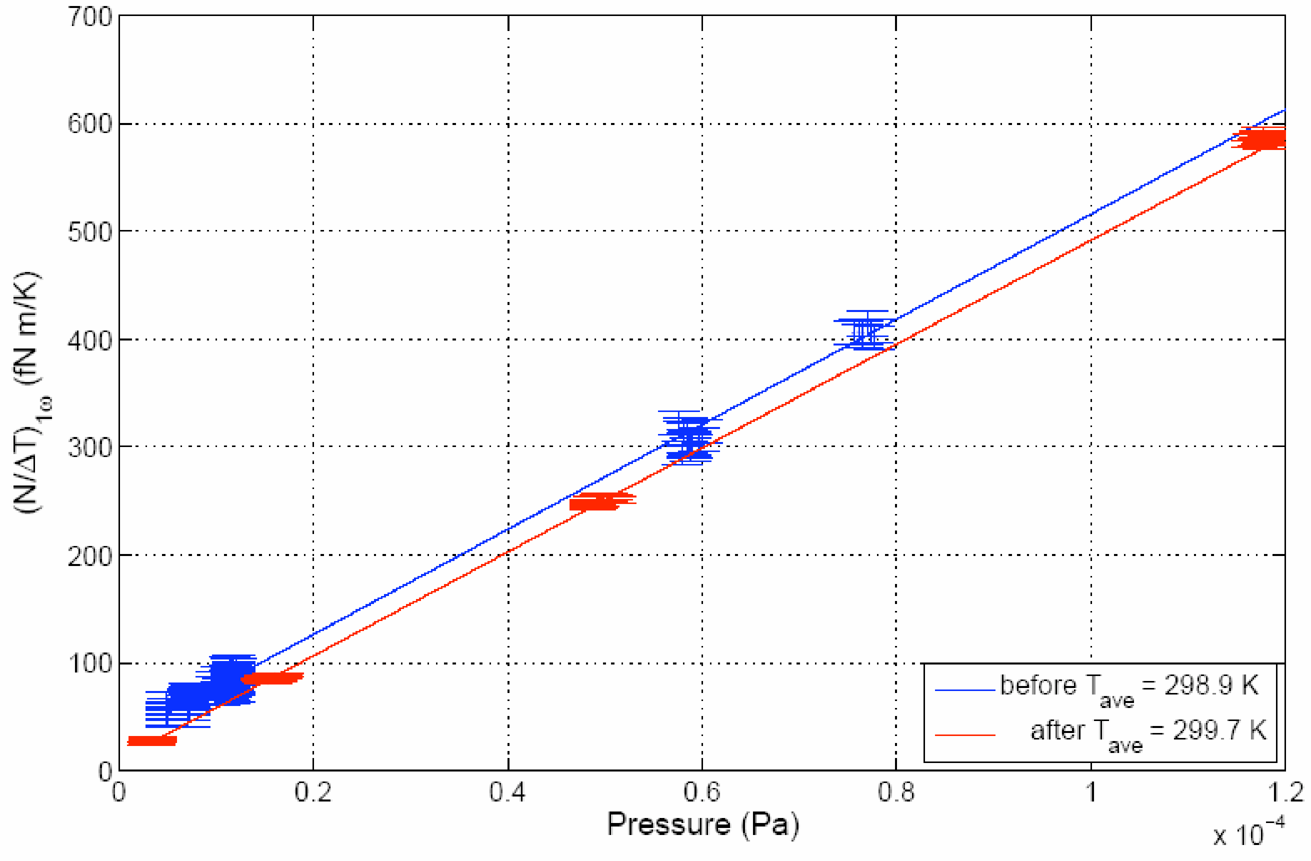
- Excess faster than radiation pressure
- Excess above 22 ℃ reaching a factor 2 the level c alculated with infinite plates model at 34 ℃
- Excess decreases with time during very mild bake-out -> suggest outgassing effect

Outgassing reduction: bake-out for prot. #1



- sensor brought quickly at T_{GRS} = 34 ℃ and maintained for days
- average pressure $P = 3.6 \cdot 10^{-6}$ Pa, radiometric effect subtracted
- 20% residual signal reduction with very mild bake-out

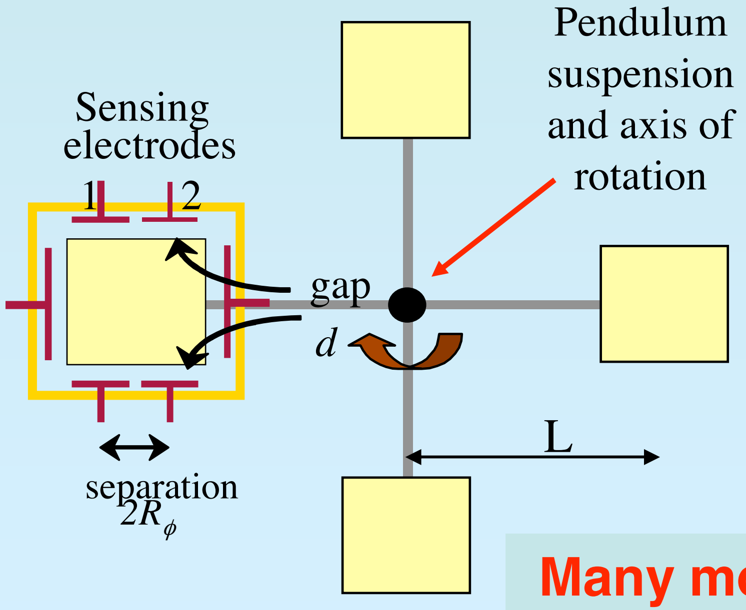
Outgassing reduction: bake-out for prot. #2

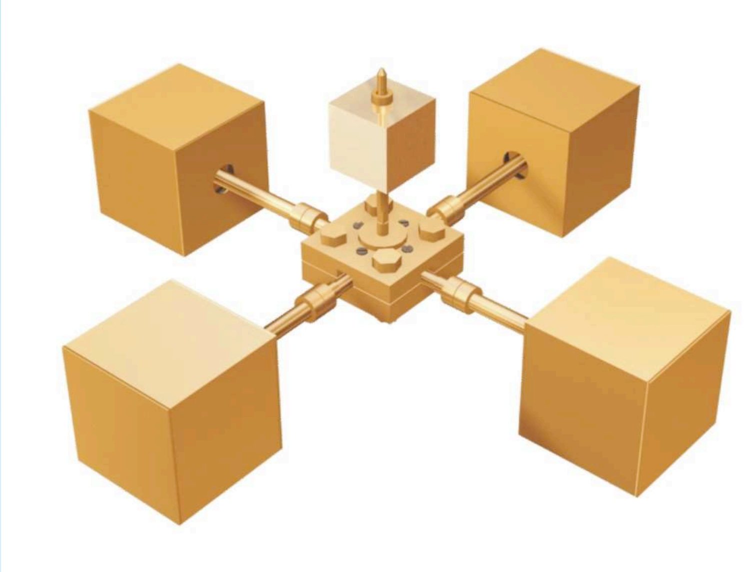


- Measurements at ~same temperature, before and after heating up to 41 ℃
- Slopes in agreement within 1%, decrease in intercept by a factor 3
- Detailed analysis and thermal modeling in progress

Direct force measurements

- Single TM configuration is not sensitive to central forces
- 4 mass TP designed, built, ready for integration with GRS prototypes
- Will allow more representative (and simple) tests in geometry and patterns
- Direct force measurements should allow also assessment of the temperature dependent outgassing





Many more details in poster by L. Carbone *et al*

Conclusions

- tests in 2 representative GRS prototypes (geometry, materials)

- measurement of radiometric effect (pressure, temperature)

- evaluation of radiation pressure for LISA (~0.5 less than infinite plates)

- zero-pressure torque excess comparable with the radiation pressure contribution (infinite plates)

- zero-pressure torque excess decreases with very mild bake-out

- we are ready to start with direct force measurements

- ground testing crucial in view of the in-flight test LTP experiments (very similar diagnostics apparatus)

- tests allow optimization of the in-flight test procedure